DOCUMENT RESUME

ED 189 178 TM 800 360

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TITLE A Case Study of the Effect of Metaphysical Commitments on the Learning of a Complex Scientific Theory.
PUB DATE Apr 80
NOTE 33p.: Paper presented at the Annual Meeting of the American Educational Research Association (64th, Boston, MA, April 7-11, 1980).

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Attitude Change: *Beliefs: Case Studies: *Concept Formation: Graduate Students: Higher Education: *Learning Theories: *Models: Problem Solving: Relativity
IDENTIFIERS Metaphysics

ABSTRACT

A model of conceptual change, adapted from Posner, is presented. It includes both the replacement of an existing concept (conceptual exchange), and the incorporation of a new concept (conceptual capture). Conceptual exchange occurs only when an existing concept is dissatisfying and a new concept is intelligible, initially plausible, and fruitful. Conceptual capture occurs if new and existing concepts separately satisfy the four conditions discussed above, and are mutually consistent. The model was applied to three interviews which were held with a graduate tutor in freshman physics: the tutor was asked to solve problems concerning Einstein's Special Theory of Relativity. The first interview was used to determine his metaphysical commitment--to a Newtonian, mechanistic view of the world: relativistic effects were explained mechanistically. The second interview showed the stability of his statements four months later and presented the metaphysics underlying relativity in comparison and contrast with his own. The third interview, ten days later, repeated parts of the first and showed that a profound change from mechanistic to a relativistic view had occurred. This case study underscores the importance of knowing a student's initial conceptions, especially those which are implicit and inarticulated, before planning a teaching strategy. (Author/CP)

A CASE STUDY OF THE EFFECT OF METAPHYSICAL COMMITMENTS ON THE LEARNING OF A COMPLEX SCIENTIFIC THEORY*

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Summary

A model of conceptual change is presented which includes both the replacement of an existing conception by a new conception ("conceptual exchange") and the incorporation of a new conception with existing conceptions ("conceptual capture"). Which alternative process occurs depends on the relative status of the existing and the new conceptions, where the status of the conception depends on whether or not it is intelligible, plausible or fruitful.

The model is applied to three interviews which were held with a graduate tutor in freshmen physics. The first interview was used to determine what metaphysical commitments he held in relation to special relativity theory and showed the significant role his commitments played in leading to the conceptual capture of counter intuitive aspects of the theory. The second interview was used to show the stability of his commitments four months later and to present the metaphysics underlying the theory in comparison and contrast with his own. The third interview, ten days later, repeated parts of the first interview and showed that significant changes in his metaphysical commitments had occurred.

* Presented at the annual meeting of the American Educational Research Association, April 1980.

1.0 THE THEORETICAL BASIS

The assumption that a person's existing knowledge plays a crucial role in determining how he or she reacts to any intellectual task underlies a rapidly growing body of research into areas such as reading comprehension, question answering, the learning of new material and problem solving. This assumption forms the basis of the work reported in this study - an investigation of the problem of understanding the conceptual change of a person learning a complex abstract subject matter.

This problem has been discussed by Posner et al. (1979) (hereinafter referred to as PSHG). They noted that recent work in the history and philosophy of science had suggested that two phases of conceptual change in a scientific discipline could be distinguished. In the first phase there are a set of central commitments which organize the advancement of knowledge in the discipline by defining problems, suggesting strategies for solving them, and specifying what count as satisfactory explanations. Kuhn (1970) refers to these central commitments as 'paradigms', and research directed by these paradigms 'normal science'. Lakatos (1970) refers to them as a scientist's 'theoretical hard core' which then generates a research program designed both to apply it (the hard core) to new experience and defend it from attack. In the second phase the central commitments themselves are under attack and in order for the discipline to proceed they must be modified or even replaced. Kuhn refers to this phase as 'revolutionary science', during which a new paradigm is acquired. For Lakatos this is a change of research program.

By drawing analogies between conceptual change in scientific disciplines and the learning of science by individuals PSHG developed a model of conceptual exchange - the process whereby a person replaces his or her central commitments. They pointed out that some of the most important of these central commitments were metaphysical in character. They also investigated the role that other metaphysical commitments played in governing conceptual change.

The study reported in this paper arose out of the work of PSHG. The purposes of this paper are to

(i) extend PSHG's model of conceptual exchange to include other aspects of conceptual change;

(ii) elaborate on the role played by a person's metaphysical commitments both in understanding counterintuitive material and in governing conceptual change;

(iii) study the effectiveness of instruction explicitly related to a person's metaphysical commitments in bringing about significant changes in those commitments; and

(iv) apply the model of conceptual change to these commitment changes.

1.1 Preliminary Comments

There are of course, different ways in which a person's conceptions could change. There could be the introduction of new conceptions through development by the person concerned, through further experience, through contact with other people, etc. There could be reorganization of existing conceptions, triggered both externally by some new idea, etc or internally as the result of some process of thought. There could be the rejection of some existing conception perhaps as a result of a conceptual reorganization, perhaps because of displacement by some new conceptions. Obviously these ways are not independent, with one giving rise to another in complex and ever changing patterns. Since this paper is concerned with the problems of dealing with new theories, I shall take this as my starting point and discuss reorganisation and rejection as they arise.

Consider, therefore, a person with existing conceptions C which include one particular conception C_1. For example, C_1 might be a theory about a particular set of natural phenomena. This person is then faced, in some way

or another, with a conception C_2 which might be an alternative theory about the same set of phenomena. The person is then faced with a decision about C_2. The options are limited : C_2 could be rejected (either outright or until further investigation suggests otherwise), or it could be incorporated into C. There are three possibilities for incorporation: C_2 could be rotely memorized with no attempt to reconcile it with C; it could replace C_1 and be reconciled with the remainder of C; and it could be reconciled with both C and C_1. Of these three incorporation possibilities I shall not be considering rote memorization since in the context of this paper it is of very limited interest. I shall call the process in which C_1 is replaced by C_2 conceptual exchange, and the process in which C_2 is incorporated by reconciliation conceptual capture. A more precise meaning will be given to these terms by the later discussion.

There could be considerable differences between different examples of conceptual exchange or of conceptual capture. On one hand the belief that there are no elephants in the city zoo would be changed without any fuss upon the arrival of two elephants from elsewhere. On the other hand, the change from a belief in a geocentric to a heliocentric solar system, while still being an example of a conceptual exchange, would have an effect far wider than that caused by the arrival of two elephants if for the person concerned it held a position as central, as important as it did for Copernicus and Galileo. PSHG chose to focus on such large scale conceptual exchanges, and presented a model of conceptual exchange[1] which was the starting point for the work reported in this paper.

1.2 PSHG's Model of Conceptual Exchange

The model presented by PSHG considers the case of a person whose existing conceptions, C_1, are challenged by a new conception, C_2. Before C_1 can be replaced by C_2, it is necessary that four conditions be satisfied: (the letters in parenthesis serve to identify conditions as they are used later).

(i) There must be some dissatisfaction with C_1 (D): A person with existing conceptions C_1 is not going to exchange them for C_2 without good reason to be dissatisfied with C_1. Dissatisfaction can occur in two possible ways. Firstly, it occurs when it becomes clear that C_1 is unable to be reconciled with new knowledge and new experiences which cannot be ignored. In other words conceptual capture cannot occur, the new ideas are said to be anomaloue, and the person holding C_1 is said to experience an anomaly i.e. he or she is unable to make sense of what is new. Secondly, dissatisfaction can occur within C_1 itself, if it is seen to violate some epistemological standard, such as appearing inelegant or clumsy, or containing ad hoc assumptions, or being unnecessarily complicated.

(ii) The new conception, C_2, must be intelligible (I): A person who is faced with a new conception, will not be able to incorporate it rationally into his or her existing conceptions if he or she cannot make sense of it. The only way in which it could be incorporated thus is by rote memorization. In order to find C_2 intelligible, the person concerned has to be able to identify or construct a coherent representation of C_2. This would also require that the person be able to see that C_2 was internally consistent, although it would not necessarily be seen to be consistent with other knowledge. Thus it is possible for the person to say that C_2 was intelligible but that he or she did not believe in it. One can appreciate Tolkein without believing in his world.

(iii) The new conception, C_2, must be initially plausible (P): A person who is faced with a new conception which is to be rationally incorporated into his or her existing conceptions must be able to see that a world in which C_2 is true is reconcilable with his or her own conception of the world. Such a conception would possess initial plausibility. It would be consistent with the person's other knowledge, as well as being internally consistent. Thus the plausibility of C_2 presupposes that it is intelligible - one cannot say that it is true without being able to understand it. But if intelligibility

is necessary for plausibility, it is not sufficient - there is also the need for C_2 to be true.

(iv) The new conception, C_2, must be fruitful (F): A person who is faced with a new conception is not going to incorporate it without good reason particularly if it is at the expense of an existing conception. In other words, he or she has to find it fruitful. There are a number of ways in which it could be so. It could be that it solves problems experienced by C_1, i.e. what is anomalous with respect to C_1 is no longer anomalous with respect to C_2. In such a case simply being plausible is sufficient for C_2 also to be fruitful. It could be that C_2 suggests new approaches, new experiments. In such a case being fruitful means more than being plausible. It could be that C_2 is more elegant, more parsimonious, more economical than C_1 and therefore to be preferred to C_1. In these possibilities the reasons for the choice of C_2 are intrinsic to it. For such a person, C_2 is fruitful. But he or she might choose C_2 for some extrinsic purpose without being personally aware of its full potential: it might be a generally accepted part of the discipline, or associated with some respected figure. In such a case, of course, C_2 might not be plausible or even intelligible (though there would be plenty of motivation to find it so) and it could not be regarded as fruitful. Thus if there is no advantage gained, no increased understanding achieved, no unsolved problems cleared up, the effort required to incorporate C_2, particularly if it involved replacing C_1, will not be made.

In discussing these four conditions, PSHG considered the different situations in which conceptual exchange might occur, and concluded that it was not necessarily a linear process in which each condition was satisfied in turn. Figure 1 shows how they depicted the possible relationships of the four conditions.

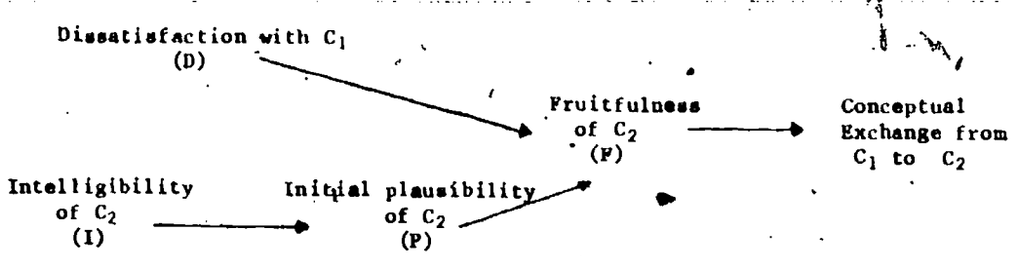
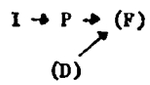


Figure 1: A Model of Conceptual Exchange. The model incorporates four necessary conditions for conceptual exchange.

They then identified three different situations in which conceptual exchange could occur.. The first two are appropriate for practising scientists, and the third for students. Firstly a scientist might be involved in the development of a theory. This is clearly a creative role. Einstein's development of relativity is a case in point. Secondly, the scientist working in a field may be presented with another person's theory. He or she is then involved in theory choice, and will need to play a critical, evaluative role. Einstein's colleagues would have been in this position. Thirdly a student meets a theory in a course of study and thus is involved in learning a theory. A conceptual exchange would be required of a student with a Newtonian view of the world who is required to learn relativity.

In considering each of these three situations in the light of the model presented in Figure 1, PSHG identified a number of commonalities but also some striking contrasts. For both theory choice and theory development dissatisfaction with C_1 is of crucial importance, but need not be so for theory learning, particularly for students who have not learned C_1. Intelligibility is necessary in all three situations, but for theory development it presents no problem - a scientist cannot develop a theory he or she finds unintelligible. In theory choice and theory learning, however, it is crucial. Initial plausibility is clearly necessary in all three situations. Finally while scientists would certainly need to find C_2 fruitful, this need not be the case for students who may well be motivated by other factors, extrinsic to C_2. To summarize these points then, the model of conceptual change by theory

development would be D → (I) → P → F, by theory choice would be D → I → P → F and by theory learning would be



where a condition in parenthesis e.g. (D) indicates the possibility that its role in the conceptual exchange process need not be critical.

In presenting the above model, PSHG made it clear that it was vastly over-simplified. The process of conceptual exchange, they pointed out, does not occur instantaneously for any one person, nor in the same way for different people, Since any basic conception is so complex, certain aspects of it might be more intelligible, plausible and apparently fruitful than others. Thus conceptual exchange "is best described as a process of gradual adjustment in one's conceptions, each new adjustment laying the groundwork for further adjustments", rather than the passage through discrete stages implied by the model.

1.3 A Model of Conceptual Change

The model of conceptual exchange outlined above started with the premise that C_1 and C_2 were irreconcilable. If this condition, however, is relaxed, the model can easily be modified to include conceptual capture as well as conceptual exchange.

As before consider a person with existing conceptions C which include one particular conception C_1. This person is faced with a conception C_2 about which a decision must be taken : whether it should be rejected or incorporated by means of rote memorization, conceptual capture or conceptual exchange.

The decision which is taken about C_2 depends on the answers to three questions: What is the status of C_1? What is the status of C_2? Can C_2 be reconciled with C_1? The answers to the first two questions will depend on which of the four conditions discussed above i.e. dissatisfaction, intelligibility, initial plausibility and fruitfulness, are met by C_1 and, separately, by C_2.

The answer to the third question will depend on whether C_1 and C_2 meet a fifth condition, mutual consistency. The model thus requires further discussion of two terms, viz. status and mutual consistency.

Within the model, the status of a conception is considered to be intelligible (I), intelligible and plausible (IP) or intelligible, plausible and fruitful (IPF). As discussed before a conception cannot be fruitful without being plausible, and cannot be plausible without being intelligible.

Two conceptions, C_1 and C_2, can be mutually consistent for any particular person only if they are both seen to be intelligible i.e. internally consistent. Only then is he or she able to decide whether they are consistent with each other. If in addition C_1, say, is plausible, then it can only be mutually consistent with C_2 if C_2 is also plausible. Thus for mutually consistent conceptions, both are plausible, or neither is. In practice, it could be that C_2 becomes plausible because it is seen to be reconcilable with a plausible existing conception. Alternatively, the reconciliation might depend on both conceptions first being seen to be plausible.

The three questions upon which the decision about C_2 is made are not necessarily independent of one another, as the discussion of the plausibility-mutual consistency relationship shows. In other words the status of one conception may very well depend on the status of the other through considerations of their mutual consistency.

The decisions which would be made about C_2 on the basis of the answers to the three questions above are summarized in Figure 2 where consideration has been given to the possible interdependence of the two conceptions. This is shown by the exclusion of certain possibilities in Figure 2; e.g. C_1 and C_2 cannot both have status IP and not be mutually consistent as discussed above. These decisions would be made on the basis of the status of C_1 and C_2 at a given

C_1 \ C_2		Status of new conception					
		I		IP		IPF	
		not MC	MC	not MC	MC	not MC	MC
Status of Existing Conception	I	R	R	CE		CE	
	IP	R			R, CC		CC
	IPF	R			R, CC		CC

I - intelligible

IP - intelligible and plausible

IPF - intelligible, plausible and fruitful

MC - mutually consistent

not MC - not mutually consistent

R - reject

CC - conceptual capture

CE - conceptual exchange

Figure 2 : A Model of Conceptual Change. Decisions made about a new conception C_2 as a function of conception status.

time. They do not imply finality i.e. a different decision could be made at a later stage if the status of one or other conception were to change. Thus if C_1 has status IPF and C_2 has status I (since only C_1 is plausible, they cannot be mutually consistent), C_2 has to be rejected. If at a later stage it is seen to be plausible (and thus consistent with C_1), then it might be incorporated by conceptual capture. Since an effort is required for conceptual capture, and C_2 is not seen as fruitful, there would probably have to be some external motivation for conceptual capture to occur. Failing that C_2 would probably still be rejected. If finally, C_2 was found to be fruitful after all, then conceptual capture would occur.

Figure 2, then, gives the decisions which would be made about C_2 at any given time, but shows nothing of the dynamic aspects of the model i.e. how the status of a conception changes. The status is dependent among other things, on the extent to which there is some dissatisfaction with it. For an existing conception C_1 dissatisfaction might arise because C_1 is unable to stimulate new directions i.e. it is no longer fruitful. It might arise because C_1 is unable to provide a basis for making sense of new information, which

cannot be ignored i.e. which is anomalous. Thus it is no longer plausible. It might arise because C_1 is seen to be clumsy, inelegant or contains ad hoc assumptions. In such a case, a drop in status probably only occurs if a satisfactory alternative exists. In other words, dissatisfaction with C_1 is directly related to its being seen as no longer fruitful, or more seriously as no longer plausible. It is unlikely that it be seen as no longer intelligible. Alternatively dissatisfaction with a new conception C_2 might arise because C_2 carries implications which appear to be unacceptable from the perspective of the existing conception i.e. C_2 is seen as implausible, counterintuitive. It might arise because C_2 doesn't appear to bring any new insights, solve existing problems, suggest new directions i.e. it is not fruitful. Thus both with respect to C_1 and C_2, dissatisfaction and status are directly related: dissatisfaction results from loss of fruitfulness and plausibility and the reduction of dissatisfaction comes with increasing plausibility and fruitfulness.

The interviews analyzed later in this paper will carry the burden of providing a more detailed understanding of the model by showing how it might be applied to specific examples.

There is one major qualification of the model which I have presented: it is, of course, a drastic over-simplification to present intelligibility, plausibility, fruitfulness and mutual consistency as discrete properties of conceptions. Since conceptual capture and conceptual exchange are generally gradual processes occurring in different aspects of any changing conception at different times, a conception is generally neither totally plausible nor totally implausible but becomes more or less plausible over a period of time. Nevertheless, particularly in the early stages of the development of a model, the simplification of presenting it in discrete terms can serve to illuminate its key elements. In addition as the examples show, at particular stages of a conceptual change the approximation to a discrete status is a good one.

1.4 A Basis for Decision Making

In order for decisions to be made about the different conditions discussed above, it is necessary that there be a basis for decision making. Toulmin (1972) considers that the current population of scientific conceptions and disciplinary problems functions as a conceptual ecology which selects in favour of some conceptions and against others. At any given stage only a very small part of the conceptual ecology might be considered to be at risk, but in principle no part of it would be immune from criticism.

Some of the most important constituents of an individual's conceptual ecology which influence and are involved in conceptual change were found by PSHG to be the metaphysical commitments held by the individual. These commitments are metaphysical in the sense that they are not susceptible to direct empirical refutation. Such commitments fall into different categories, and are summarized by PSHG as follows:

(1) Epistemological Commitments

(1a) Explanatory ideals: Most fields have some subject-matter-specific views concerning what counts as a successful explanation in the field.

(1b) General views about the character of knowledge: Some standards for successful knowledge such as elegance, economy, parsimony, and not being ad hoc seem subject-matter-neutral.

(2) Metaphysical Beliefs and Concepts

(2a) Metaphysical beliefs about science: Beliefs concerning the extent of orderliness, symmetry, or non-randomness of the universe are often important in scientific work and can result in epistemological views which in turn can select or reject particular kinds of explanations. Such beliefs played a large role in Einstein's thought. Beliefs about the relations between science and commonplace experience are also important here.

(2b) Metaphysical concepts of science: Specific scientific concepts often have a metaphysical quality in that they are beliefs about the

ultimate nature of the universe and are immune from direct empirical refutation. A belief in absolute space or time is an example.

Thus a conception could be fruitful because it suggests new ways of relating science and commonplace experience. It could be plausible because it is consistent with some belief about the ultimate nature of the universe, because it is elegant and parsimonious. It could cease to be plausible because if conflicts with other knowledge, or because it includes too many ad hoc assumptions, etc.

PSHG also noted that it was not sufficient to state that an individual had a commitment to, say, absolute time in order to take a decision about a conception. It was also necessary to take into account the strength of that commitment. For example, a person learning special relativity has to accept the relativity of time. If for the person concerned, however, the belief in absolute time is strong enough, and if the arguments presented in support of relative time carry insufficient weight then he or she will consider that the existing conception still is plausible and the only way in which the new conception can be incorporated is through some reconciliatory procedure.

Metaphysical commitments, then, and the strengths with which they are held play a critical role in the decisions made about new and existing conceptions. This role will be further illuminated in the discussion of the results.

2.0 METHODS AND DATA

The research reported in this paper is based on a single case study. A graduate student (SL), tutoring in a freshman non-calculus physics course (P101) was interviewed on three separate occasions about one of the units in the course-special relativity. The first interview was used to analyze SL's metaphysical commitments with respect to special relativity, the second interview held five months later was used firstly to check whether these commitments had remained constant and secondly to intervene directly in an attempt to influence these commitments, and the third interview held ten days after the second was used to see whether there had been any changes to SL's commitments arising from the second interview.

In the first interview, conducted after SL had tutored this unit for the second time, he began by discussing how he viewed two seemingly counterintuitive propositions of the theory, viz. moving clocks run slow and moving rods shrink. I then presented two problems to him and asked him to solve them while thinking aloud. At each stage I asked him to give reasons for his answers, but I made no attempt to teach him. The problems, though simple to state, involved the major components of the theory. The first problem considered the workings of a light clock and the implications it has for the concept of time. The second problem involved simultaneity and the synchronization of distant clocks. This was followed by presenting SL with written explanations from two different points of view. After he had read these explanations, I asked him without prior warning to repeat them from memory as a comprehension exercise[2].

The second interview was conducted five months after the first one while SL was tutoring the unit on special relativity for the third time. In the first part of the interview I reiterated the major points which SL had raised in the first interview and asked him to discuss them to determine to what extent there had been any change in his metaphysical commitments in the intervening time. In the second part of the interview I presented some of the basic elements of special relativity and contrasted them with the results of my analysis of the first interview, showing where I saw differences and presenting arguments

in support of special relativity. In essence SL had attempted to reconcile the results of special relativity with his Newtonian foundation, and I sought to show what I understood the Einsteinian foundations to be.

The third interview was conducted ten days after the second interview during which time SL had had numerous discussions with students he was tutoring. He had also come to me on two occasions for clarification of details, and discussion of specific problems set in the unit. In the interview I again reiterated the major points which SL had raised in the first two interviews and asked him to comment on how he viewed the propositions of special relativity viz. moving clocks run slow and moving rods shrink. The discussion proceeded along lines similar to the first. As before I used the recorded discussion to analyze SL's current metaphysical commitments.

3.0 RESULTS

The purpose of this section is to analyze and discuss the role of metaphysical commitments in assisting conceptual capture of counterintuitive results, to investigate the conditions under which they are replaced in the process of conceptual exchange and to apply the model of conceptual change outlined above to these results. It is, however, impossible to discuss the role of such metaphysical commitments in detail without simultaneously discussing their content. I shall nevertheless attempt to restrict all discussions of content to the instrumental role which it plays, and leave any comment about its intrinsic value to others.

3.1 Analysis of SL's initial conceptions[3]

The analysis of the relevant parts of SL's initial conceptions (including C_1 and possibly other parts of C) is based primarily on his responses during the first interview with appropriate corroboration from the second interview to demonstrate the stability of these conceptions over a period of some five months.

In the time prior to the first interview SL would have been required as a physics graduate student and as a tutor in P101 to make some sense of Einstein's Special Theory of Relativity (STR). He would probably not have considered the option of claiming that it was nonsense - such a path does not usually lead to success in graduate school - and thus he would, probably implicitly, have set himself the task of reconciling STR with his existing physics knowledge. The evidence I shall present below suggests that his primary concern was with the two propositions which run directly counter to common experience (viz. moving clocks run slow (time dilation); moving rods shrink (length contraction)), rather than with the theory as a whole. His formal physics knowledge would undoubtedly be influenced by the large component of Newtonian physics his education must have included. SL's initial conceptions are the product of Einsteinian branches grafted to Newtonian roots.

SL shows a firm Newtonian commitment to a mechanistic view of the world in which objects have fixed properties such as length, mass etc. and in which explanations of phenomena (including relativistic effects) should be given in terms of these objects and their interactions (i.e. in mechanistic terms). In talking about the question of shrinking rods and slowing clocks, he says:

> (SL) I see them as being--as changing their length, or changing their time. But I can talk to the person who's moving at the same velocity as the stick and the clock. He's telling me that they don't change.....I feel they haven't changed, but the way I'm looking at them has changed..... I guess I'm allowing for the fact that a person who's seeing these things at rest, who has his clock at rest, his meter stick at rest, has [pause] a little more right to say what is really happening to the sticks. (emphasis added)

A little later he continues:

> (SL) But I'm not at all uncomfortable with the idea of foreshortening. I do say, I do feel it is a perception. I will say it is a shortening. I know in the back of my mind that my friend who's riding along with that meter stick is telling me all the time that as far as he can tell, it's the same length and I believe what he's saying, which is o.k.
>
> (I) It's not a conflict?
>
> (SL) No, because the fact that it's moving makes it appear to me as if it were foreshortened. (emphasis added)

Here SL insists on treating length as constant, independent of frames of reference. He is, thus, led to treat the special theory's claims concerning the relativity of length as simply a distortion of perception.

In the second interview SL reiterates this same point in somewhat different terms. Discussing the question of what the reality of an object is, he says:

> (SL) But when you start talking about reality....I sort of like the idea of thinking of an absolute reality sort of independent of observation.

He then spontaneously introduces the example of a vector, something which is characterised by its length (and direction) and continues:

> (SL) If you can think of it [the vector] as something independent of coordinate systems, you have space and you have something out there and it has physical reality independent of how you measure it.

Thus, at this stage, SL is committed to a view of the world in which objects have an independent reality one manifestation of which is a constant length independent of how or even whether it is measured.

The next topic I shall consider concerns the nature of the explanations which SL provides of relativistic phenomena. The issue arises out of SL's consideration of the light clock problem. This is important because it provides him with the plausible mechanism for explaining time dilation that his metaphysics requires him to look for. He can thus see why a moving light clock runs slower. He correctly predicts that another clock which does not depend on light moving with the light clock also runs slower.

> (SL) It will be keeping the same time [as the moving light clock]. I haven't done anything to it that it shouldn't keep the same time.

I then asked him to explain why this should be the case.

> (I) But now we've got a [clock] which has nothing whatsoever to do with light and so how can you explain the fact that it is running slower as well?
>
> (SL) Well, that I can't do, but you-- let's see, if you use another clock, well, like a human heartbeat is also a clock and in detail I can't explain why that would go slower.....but I have a little bit more of a feel that it depends on the speed of light. For instance, if you are sending--your body runs by sending neural stimulation, up through your body--those are electrical phenomena....well, it's a phenomenon which depends on light and electricity, then I reason that those processes will be affected similar to a light clock and so I can more or less see how the heartbeat would slow down if it's moving at a high velocity. (emphasis added)

Later, I questioned SL again on this issue:

> (I) I'm suggesting that perhaps you can't argue for your clock on the basis of light.
>
> (SL) I don't see how in depth I can argue for my clock on the basis of light, but I believe it can be done.

With respect to this same question of what constitutes a satisfactory explanation we had the following discussion in the second interview

> (SL) I don't like the idea of faith so much....I think that physics works, can explain everything, and that's the premise I'm working on and so when I come up with something that I can't understand I would like to think it through and explain it to myself.....if someone just tells me well these mechanical clocks have to [run slower], that doesn't sit well with me because I can't see why they're telling me to take something on faith when I or they can't explain it.

(I) OK so - I think that it comes down to what you would accept as a reasonable explanation of this phenomenon which we can agree about which is that a clock slows down. And what is, as far as you're concerned, a reasonable explanation of such a phenomenon has to do with being able to postulate some sort of process, a mechanism which makes things slow down?

(S) Yes

(I) And that underlying everything in the world there is this type of mechanism explanation?

(S) Right

The analysis of SL's initial conceptions shows that he has a metaphysical commitment to a mechanistic view of the world. This is shown firstly by his commitment to the fixed properties of extended objects being the fundamental reality in nature. Thus a meter stick has a fixed length and any observations which show otherwise are perceptions so that it appears to the observer as if it were shorter. Secondly he is committed to the principle that any explanation of relativistic effects must be given in mechanistic terms. Since he has an account of the slowing down of a light clock, he can and does use this to explain all other problems of time dilation by assuming that they somehow depend on light.

3.2 Application of the model to SL's initial conceptions

The model of conceptual change presented earlier is applicable to SL's initial conceptions, to the fact that he has been able to incorporate two counterintuitive propositions into his set of conceptions about the world of appropriate phenomena. I shall assume that within SL's set of conceptions, C, there is a subset, C_1, which includes conceptions about the reality of objects and the nature of satisfactory explanations of natural phenomena. Since there is a lack of evidence to the contrary, I shall assume that for SL, C_1 is both intelligible and plausible. Whether it is, for SL, a fruitful set of conceptions is a more open question to which I shall return.

Consider that SL now comes to learn special relativity. For our purposes I shall only consider the second postulate - that of the constancy of the speed of light - and the two propositions of time dilation and length contraction.

All the interview evidence shows that SL accepts the second postulate without question. He simply uses it without any discussion. I shall assume that it is a constituent part of C. The two propositions are, however, controversial, and form the set of conceptions, C_2. The outline of the model in Figure 2 indicates that the only way in which C_2 can be incorporated into C with C_1 having status IP (or IPF) is by means of conceptual capture. This can only happen if C_2 is made plausible through reconciliation with C_1 i.e. if C_1 and C_2 are seen as being mutually consistent.

SL manages to reconcile C_2 with C_1 by making two auxiliary assumptions: that a shrinking rod constitutes a perceptual problem and doesn't actually shrink ("I feel they [rods and clocks] haven't changed, but the way I'm looking at them has changed") and that the light clock problem provides him with a plausible mechanism for explaining time dilation even though he cannot see the details in every case in which clocks run slower ("I don't see how in depth.... but I believe it can be done").

The only element then lacking in explaining the conceptual capture of C_2 is the motivation. In principle it could happen - C_1 and C_2 have been reconciled (at least to SL's satisfaction), and both have status IP - in practice there needs to be a reason for SL making the effort necessary. Here the obvious candidate is the importance of relativity theory. If SL wants to make his way in physics, he has to come to terms with relativity. As a graduate student he has to learn it, as a tutor he has to teach it to his students.

One final point concerns the status of C_1 - it need only have been IP before C_2's capture, but more than likely its role in the capture would be enough for its status to be raised to IPF. Whether or not this is the case, however, makes no difference here.

3.3 Analysis of the intervention

The purpose of the intervention in the second interview was to influence SL's understanding of relativistic phenomena in order to bring it more into line with what I understood to be the orthodox Einsteinian position. The

rationale I adopted was that of presenting him with the position he had adopted (based on the previous analysis), contrasting it with the Einsteinian position and stressing the advantages this had over his point of view. At each stage we discussed and attempted to clarify the points which had been raised.

The content of this intervention centred on the issue of what the fundamental reality of the world might be. SL had indicated that he saw this in terms of objects and their interrelationships, and I presented the point of view that events were more fundamental and that length, say, could be interpreted in terms of events i.e. something that is localized in space and time. For instance, length was the spatial separation of two events happening at the same time: viz. the two measurements of the ends of a meter stick. I showed that two direct consequences of this point of view, coupled with the postulate of the constancy of the speed of light, were disagreements between two people moving relative to each other about the length of time between any two events, and about which two events were appropriate in length measurement. Thus a regard for events as the fundamental reality led directly to time dilation and length contraction in an internally consistent way without the necessity of the assumptions SL had made in order to achieve the reconciliation discussed in the previous section.

A second part to the issue of fundamental reality dealt with queries raised by SL in the interview. Was the focussing on events as reality not a denial of the existence of objects? Or in his own words

(SL) Then how do you talk about its reality? Just in terms that there are two events that happen?

This alerted me to a possible misinterpretation of the new concept of length, and led into a discussion of the detailed implications of the changes which I had outlined, implications which had not occurred to me or which did not seem to be central, but which were clearly important to SL. A reinterpretation of length which was internally consistent was certainly required, but with the additional requirement that it be consistent with SL's other conceptions.

3.4 Application of the model to the intervention

In order to go from the incorporation of the two relativistic propositions by means of conceptual capture to their incorporation by means of conceptual exchange, at least three conditions have to be met : the status of SL's initial conceptions C_1 has to drop, concomitantly the reconciliation between C_1 and C_2, has to break down, and the status of C_2 has, at least, to be maintained but preferably raised.

Since the analysis of the next section will show that conceptual exchange did occur we can assume that these conditions were met. This, however, is indirect evidence, and in support of the claim that the intervention was the instrumental factor in the exchange, I shall indicate how these conditions could have been met as a direct result of the intervention.

As I discussed while introduoing the model, status lowering is directly related to dissatisfaction with the conception. In this case there has been no anomaly. The alternative presented to SL has, however, shown that the auxiliary assumptions made in order to reconcile C_1 and C_2 are unnecessary - it is possible to understand the relativistic propoaitions without them. It is important to realise that these aesumptions were not shown to be wrong - merely unnecessary. That this appeared to create enough dissatisfaction to lead to a lowering of the status of C_1 is an implicit indication of the existence, with sufficient strength, of an epistemological commitment to the economy of a theory. One factor, then, which leads to dissatisfaction with C_1 and the consequent lowering of its status is the realization that the auxiliary assumptions can be discarded, in the process of which the reconciliation between C_1 and C_2 has to break down. Thus two of the conditions listed above could have been met simultaneously.

The importance of lowering the status of C_1 must not be overlooked - without it, there can be no conceptual exchange. The source of dissatisfaction discussed above is appealing because it could account for two conditions, but it might

not be sufficient. The argument which showed that the two auxiliary assumptions were unnecessary dealt with the internal self-consistency (or lack of it) of the conceptions under discussion. Equally important for the existing conceptions was the external support they received from extensive experience, that which made them plausible. Thus SL might well have wondered whether he had to discard a concept of length which had served him well in all areas other than relativity. In other words, he might not be prepared to find C_1 implausible until he had found C_2 to be plausible : that interpreting common experience with C_2 made sense. In other words there is an important link between the first and third conditions above.

In order to check whether the third condition could have been met, we need to consider the new conception, C_2. In the discussion of SL's initial conceptions, C_2 consisted solely of the two relativistic propositions. This must now be expanded to include the conception of events as fundamental if a satisfactory exchange is to occur. As I discussed above this conception leads directly to the two propositions so C_2 is internally consistent and could thus be intelligible. The effect of the second part of the discussion outlined above i.e. the reinterpretation of the concept of length, could then be to make C_2 plausible. This being the case, a possible barrier to C_1's status reduction would have been removed. There would also be the external motivation arising from the necessity to find relativity plausible in order to feel a part of the physics community. Thus the third condition needed to open the way to conceptual exchange could have been met.

3.5 Analysis of SL's final conceptions

The analysis of the conceptions which SL held after my intervention follows that above. Thus I shall be looking at the same points which were summarised at the end of the analysis of SL's initial conceptions.

Firstly, there is the question of what reality is. The analysis showed SL's initial commitment to objects with fixed properties such as length and mass. Part of the evidence to support the initial analysis came from SL's view (repeated at least three times throughout a lengthy interview) that he would give "a priority of claim to the person [at rest with respect to] the meter stick", and that it simply appears to be foreshortened because it's moving. So I put SL's initial view of the stationary observer having more right, having priority, to talk about length to him.

> (SL) Right, I don't know if he has more right.... I think even back then and that's what I said but it's not literally what I meant. What I am saying is that in a way it is easy. If I were him I would have an easy time measuring the stick..... I was almost talking about it's easy for him to measure and it hasn't been easy for me to think of how I would measure if I am moving with respect to it.

One might want to accept at face value SL's assertion that by "right" and "priority of claim" he meant "easy". But this assumes that for SL matters of principle are equivalent to matters of convenience, an assumption I think is unreasonable in the light of the rationality of the three interviews. A more appropriate assumption seems to be that SL wants to reduce the dissonance caused as a result of the change.

There is further evidence in support of this change. In discussing his changed viewpoint he reiterates one commitment which remains unchanged: there is a reality independent of measurement. What has changed is his interpretation of this commitment.

> (SL) Well, points in space are real. I was thinking about this earlier. I don't know if I've moved that far from where I was before. I always felt that there are things that are real - and how you observe them, that might change. But there are some physical realities like you have a flash bulb here and a flash bulb there. They are quite independent of whatever coordinate system you put on and I guess I've always had this feeling that I didn't like being restricted to a coordinate system and that what is there doesn't depend on whatever coordinate system I lay on it and so that would prompt me to say the remarks I made in the past about.... a meter stick [having] a certain length, that is, it occupies space independent of the coordinate system. It is physically there but now if I had to measure that, if I had to tell somebody how much space it occupied, now we have to agree on the coordinate system so that it would make some sense.

It is important to note that SL recognizes that there has been a change. Following additional questioning he explicitly indicates what he has given up:

(I) Are you saying that the property of length that it has is on a par with this idea of the reality of the meter stick?

(SL) No, that's a partial description of it, but it's not the same thing. I mean if I can talk about length independent of how I measure it, and I guess I can't.

Thus while SL still believes that there is a reality independent of measurement, he has changed his view of how that reality manifests itself. Initially, the object itself had a fixed length, but now the reality is in individual events, localized occurrences in space and time e.g. the triggering of a photographic flash bulb.

Secondly, there is the question of what constitutes a reasonable explanation of relativistic phenomena. Initially when considering time dilation SL felt that to explain why any moving clock runs more slowly it was essential to introduce some mechanism. In his case, he felt that all processes had to be light-like processes. During the course of this interview I asked him to consider a clock which keeps time with a flywheel which regularly reverses its direction. Although his explanation is a little confused, what is significant about it is that he makes no attempt to suggest that there is anything light-like about the flywheel - he simply compares the light clock and the mechanical clock whenever the flywheel reverses its direction. Once again the basic reality lies in these events.

(SL) Well, you can have two observers [O_1 and O_2].....both observers want to measure the time it takes for the [flywheel] to change direction and I will give each an identical light clock [L_1 and L_2]. A light clock [L_1] which is stationary to the [flywheel] measuring a certain time for the [flywheel] to turn around - well, an observer [O_1] who is looking at the same light clock [L_1] says.... it takes one tick of [L_1] for the [flywheel] to turn around. The flash of light goes up and down in that amount of time and the [flywheel] has changed direction. The observer [O_2] who is moving with velocity relative to [L_1] will say that [L_1]... took a shorter time than his [L_2] and the same thing [flywheel reversal] happened in the same time interval. He measures a time interval which is somewhat larger than the time interval which the stationary light clock measured, but the same events occurred across the respective time intervals. The one guy says the time interval is 1 s and the other guy says it's 1.67 s. The same thing happened. It doesn't have anything to do with the clock necessarily - it's just how you measure the idea of time. (emphasis added)

Thus time measurement has to do with intervals between events, and has nothing to do with the mechanisms used to keep time.

In a similar manner, when considering the phenomenon of length contraction SL sees it as arising from the measurement procedure, rather than from some mechanism operating between the particles of an object. Talking about someone moving with respect to him and measuring a meter stick, SL says

(SL) .....if he measures lengths the same way that I measure lengths and he has made a correct measurement, that's OK. I guess the fact that we don't measure the same length is that perhaps we are not measuring the exact same thing. We are measuring in the same way....

He then goes on to consider time dilation but returns to the question of the measurement of length as the distance between two events (or occurrences). His moving associate uses the same events, but the numbers he assigns to his measurements are different.

(SL) I make a measurement of length and I work with that according to the equations of physics and it describes what happens to me and he'll use the same laws of physics. He will use his measurements and he will discover the same occurrences. I get the feeling now that I am moving into two separate worlds really but what is the same are the things that happen - the actual sort of physical occurrences of something or other; that a light beam should race from one end of a meter stick to another and back.

(I) So you are not saying it's two different physical worlds?

(SL) No. The same thing is happening. There are just different consistent ways of describing them. (emphasis added)

The evidence shows that there has been a profound change in the nature of the explanation which SL offers, away from a concern with objects and their interactions causing relativistic effects, i.e. away from mechanistic explanations to relativistic explanations, i.e. to an awareness that these effects arise from the very process of measurement and of setting up appropriate scales.

3.6 Context of SL's Conceptual Change

The analyses presented above show that there has been a significant change in the way in which SL thinks about certain relativistic phenomena, a change in his basic metaphysical commitments. Before the intervention he looked for mechanistic explanations of relativistic phenomena in line with the fact that he was quite ready to assent to a belief that mechanistic explanations are the foundation for everything in the physical world. After the intervention there is no such universal belief. This is a profound change in one individual's conceptions which mirror, somewhat imperfectly, the change in the worldview of the scientific community.

There can be little doubt that the change from a mechanistic worldview occasioned by Einstein's theory of relativity has been of immense significance, discussed by numerous authors (see Holton (1960, 1969), Zahar (1973) , Schaffner (1974), Hirosige (1976), Posner et al (1979) and references listed therein). One part of the reason for the significance of this change rests in the importance of the mechanistic worldview for nineteenth century physics. Margenau (1978) says that the most convincing feature of the physics of that era was

> "the universality of mechanistic processes, which illuminated simultaneously the study of sound, of heat, even of light, which was regarded as a vibration in a mechanical ether" (pxxxiv)

To depart from such universality was no small upheaval which could not be avoided. Hirosige claims that

> "for the emergence of the theory of relativity a complete emancipation from the mechanistic worldview was the essential prerequisite" (p73)

and elaborates this point later, saying that

> "physicists did not generally accept [relativity], until they recognised that it was concerned not only with electrodynamics but also with mechanics, that is, that the fundamental postulates of the theory of relativity were universal principles to which mechanics as well as electrodynamics was to be subjected. Such a recognition contradicted the mechanistic worldview". (p74)

The change in SL's metaphysical commitments, then, must be regarded as highly significant. The question arises as to why it had not happened earlier, since we must assume that SL would have had access to satisfactory accounts of relativity theory through different teachers and textbooks. Here the account

of the change provided by the model discussed earlier provides a clue - conceptual exchange cannot happen unless there is sufficient dissatisfaction to lead to a lowering of the status of C_1 - SL's mechanistic worldview. Without this happening the intervention would essentially have achieved nothing.

4.0 EDUCATIONAL IMPLICATIONS

The research reported in this paper shows that a person's conceptions which include metaphysical commitments play a very significant role in the way in which he or she understands complex subject matter such as Einstein's Special Theory of Relativity. These conceptions play such a role even though they are often implicit, with the person holding them unable to articulate them in any detail. They can then constitute an unidentified barrier to greater understanding of some topic or other. Until such time as the detailed nature of this barrier or block is revealed and the person holding it sees that it is implausible, he or she will be unable to incorporate the topic satisfactorily into his or her conceptions. For example, SL's commitment to a mechanistic worldview constituted a barrier to his deeper understanding of special relativity.

Firmly held conceptions which constitute a barrier to greater understanding are not restricted to metaphysical commitments. Neither is the presence of such barriers confined to abstract subjects such as relativity. Lovell (1979) reviewed some of the literature pertaining to these issues, literature which dealt with topics such as the conceptions of the world as a cosmic body held by children aged 8-13, concepts of mechanics held by pupils aged 11-16 and concepts (or a lack thereof) of reference frames held by first year university students. In commenting on these, Lovell says

> "the alternative frameworks pupils hold regarding some situations may often be at variance with the framework which teachers wish them to elaborate from teaching, from the textbooks, or from their own experimentation".

He continues:

> "...such thinking is often resistant to attack. It is established in childhood, becomes well entrenched by adolescence and our teaching often does not eradicate it."

The problem, then, is widespread. The implications of the research reported in this paper for working towards a solution of this problem derive from the model of conceptual change. A teacher needs to know the initial conceptions of the students he or she is teaching, particularly those which

are implicit and inarticulated, before planning an appropriate teaching strategy whether it be designed to lead to conceptual capture or conceptual exchange. Using the methods which I employed in this research under the circumstances of normal teaching would impose intolerable burdens on the teacher. Further research to determine the range of possible conceptions in any group of students is clearly necessary in order to develop diagnostic instruments for the teacher. This research shows the advantage of such a diagnosis in helping to enhance greatly the effectiveness of any teaching situation.

Notes

1. Posner et al (1979) used the terms assimilation and accommodation for conceptual capture and conceptual exchange respectively. They acknowledged that these are Piaget's terms, but indicated that in using them they intended no commitment in his theories. I have introduced the terms conceptual capture and conceptual exchange firstly to eliminate all confusion on this count and secondly because current dictionary usage places them closer to their intended meaning.

2. A complete presentation of the problems is given in the Appendix contained in Posner et al (1979).

3. A less detailed analysis of SL's initial conceptions as reflected in the first interview is contained in Posner et al (1979).

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